REDUCED COMPLEXITY DECODING FOR
TRELLIS CODED MODULATION

Background of the Invention

5   1. Field of the Invention

This invention relates generally to digital communication systems and methods, and more particularly to a method of implementing a Viterbi algorithm (VA) for trellis coded modulation (TCM) decoding, optionally in association with a digital signal processor (DSP) or other data processor.

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2. Description of the Prior Art

The upstream physical layer of the new DOCSIS 2.0 specification uses advanced time-division multiple access (A-TDMA) or synchronous code-division multiple access (SCDMA) burst type formats. For SCDMA, the signal processing sequence for the

15   transmitter 10 is illustrated in Figure 1. The modulation scheme includes Reed-Solomon (RS) encoding 12, optional trellis coded modulation (TCM) coding 14, a unique SCDMA framing scheme 16, and symbol mapping 18 into various constellations depending on the TCM mode used. Furthermore, in TCM mode, a special RS-bytes to TCM-input-bits mapping is used at the TCM encoder input.

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In view of the foregoing, it would be both desirable and advantageous in receiver applications, for example burst receiver such as the SCDMA burst receiver implemented, for example, in DOCSIS2.0 standard, to provide a method of implementing a Viterbi algorithm (VA) for trellis coded modulation (TCM) decoding, optionally in association

25   with a digital signal processor (DSP) or other data processor.

Summary of the Invention

The present invention is directed to a method of implementing a Viterbi algorithm (VA) for trellis coded modulation (TCM) decoding, optionally in association with a
5   digital signal processor (DSP) or other data processor.

According to one embodiment, a method of reduced complexity TCM decoding comprises the steps of a) receiving a soft symbol; b) choosing a constellation point closet to the received soft symbol for each TCM subset; c) calculating the metric of each branch
10   based on the distance (for example squared Euclidean distance) of the chosen point from the received symbol; d) calculating new state metrics for each trellis state, as the minimum of the sums of all possible (previous state + appropriate branch) that lead to a new state; e) selecting the state with the smallest metric; and f) tracing back from the state with the smallest metric, to determine the state and appropriate transmitted
15   symbol(s) having a delay based on the traceback length, and repeating these steps for each received symbol.

According to another embodiment, the distance in step c) above is other than the squared Euclidean distance, for example that of Eq. 2 hereafter.
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According to another embodiment, step b) and c) above are performed only for some TCM subsets (for example 4 out of 8 subsets, for which the received symbol is closest to), whereas for all other subsets, the distance in step c) is replaced by a saturated distance depending on the constellation.
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According to another embodiment, step b) and c) above are performed only for some TCM subsets (for example 4 out of 8 subsets, for which the received symbol is closest to), and also the distance in step c) above is other than the squared Euclidean distance, for example that of Eq. 2 hereafter, whereas for all other subsets, the distance in
30   step c) is replaced by a saturated distance depending on the constellation.

According to another embodiment, a method comprises implementing a VA or reduced complexity VA on a DSP.

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Brief Description of the Drawings

Other aspects and features of the present invention and many of the attendant advantages of the present invention will be readily appreciated as the invention becomes

5   better understood by reference to the following detailed description when considered in connection with the accompanying drawing figures thereof and wherein:

Figure 1 illustrates a SCDMA mode signal processing sequence for a burst type transmitter;

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Figure 2 illustrates a TCM encoder for SCDMA operating mode;

Figure 3 shows an 8-state, 2-branch trellis for SCDMA operating mode with QPSK constellation;

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Figure 4 shows graphical simulation results for uncoded operation and also for various TCM coding in the transmitter for SCDMA operating mode using one information bit per symbol;

20   Figure 5 shows graphical simulation results for uncoded operation and also for various TCM coding in the transmitter for SCDMA operating mode using two information bits per symbol;

Figure 6 shows graphical simulation results for uncoded operation and also for

25   various TCM coding in the transmitter for SCDMA operating mode using three information bits per symbol;

Figure 7 shows graphical simulation results for uncoded operation and also for various TCM coding in the transmitter for SCDMA operating mode using four

30   information bits per symbol;

Figure 8 shows graphical simulation results for uncoded operation and also for various TCM coding in the transmitter for SCDMA operating mode using five information bits per symbol;

5   Figure 9 shows graphical simulation results for uncoded operation and also for various TCM coding in the transmitter for SCDMA operating mode using six information bits per symbol;

Figure 10 depicts an example of TCM region partitioning for a 16QAM

10   constellation; and

Figure 11 shows an 8-state, 4-branch trellis for SCDMA operating mode with constellation other than QPSK.

15   While the above-identified drawing figures set forth particular embodiments, other embodiments of the present invention are also contemplated, as noted in the discussion. In all cases, this disclosure presents illustrated embodiments of the present invention by way of representation and not limitation. Numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and

20   spirit of the principles of this invention.

Detailed Description of the Preferred Embodiments

TCM Coding scheme in SCDMA

In the SCDMA operating mode, the cable modem (CM) must support trellis

5   coded modulation (TCM) for transmission of 1,2,3,4,5, or 6 information bits per symbol

using QPSK, 8QAM, 16QAM, 32QAM, 64QAM, and 128QAM respectively. Figure 2

shows an 8-state TCM encoder 106 that was employed by the present inventors during a

simulation. The convolutional encoder is of rate 1/2 for QPSK and rate 2/3 for all other

constellations. Hence, there are four subsets for QPSK and eight subsets for all other

10   constellations. The uncoded bits are used to select between constellation points in the

same subset. The respective trellis is depicted in Figure 3 for QPSK (with 8 states, 2

branches leaving each state) and in Figure 11 for non-QPSK constellations (with 8 states,

4 branches leaving each state).

15   TCM Coding in the Transmitter, VA Decoding in the Receiver

This is the optimal receiver operation for the coding subsystem, when TCM

encoding is turned on. The decoder uses Viterbi algorithm, with 8-state trellis and 2 or 4

branches leaving each state for QPSK and all other constellations respectively. Basically

there are 8 slicing operations (none for QPSK and 8QAM), and 8 branch metric

20   calculations (4 for QPSK) for each iteration. For state metric calculations there are (4

branch * 8 state) = 32 additions, and for each state 4 comparisons to derive the best

previous state. A thorough description and considerations regarding implementation on

DSP are discussed herein below. This suggests that 16 clocks are needed per symbol to

perform the branch metric calculation. The branch metric calculation is based on the

25   square Euclidean distance between the received symbol and the closest symbol in each

subset, and follows Equation (1) below.

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Eq. (1): Branch metric calculation for full VA

$$B_i = \|z - \hat{a}_i\|^2 \qquad i = \begin{cases} 0,1,2,3 & \textit{for QPSK} \\ 0,1,2,3,4,5,6,7 & \textit{for all other constellations} \end{cases}$$

Where :

B_i is the branch metric for the i'th subset

z is the received soft symbol

$\hat{a}_i$ is the constellation symbol belonging to the i'th subset, which is closest to the received symbol.

5   TCM Coding In the Transmitter, Simplified Metric VA (SMVA) Decoding in the

Receiver

This is a novel suboptimal receiver operation for a TCM modulation subsystem.

One example is described herein below for an 8-state TCM code used in SCDMA

transmission associated with the Docsis2.0 standard. The present invention is not so

10   limited however, and it shall be understood the method described is general.

The decoder uses a simplified metric Viterbi algorithm (SMVA), with an 8-state

trellis and 2 or 4 branches leaving each state for QPSK and all other constellations

respectively. Basically, there are 8 slicing operations (no slicing for QPSK and 8QAM),

15   and 8 branch metric calculations (4 for QPSK) for each iteration. For state metric

calculations, there are (4 branch * 8 state) = 32 additions, and for each state, 4

comparisons to derive the best previous state. A thorough description and considerations

regarding implementation on DSP are discussed herein below. In SMVA, the branch

metric is calculated by using a simplified metric for the distance between the received

20   soft symbol and the closest symbol in each subset. One option for a simplified metric is

adding the absolute value of the real and imaginary parts of the complex vector resulting

from the subtraction of the received symbol and the closest symbol in each subset, and

follows Equation 2 below. Following DSP implementation, the number of clock cycles

needed per symbol to perform the simplified branch metric calculation is reduced from 16

25   to 8. The degradation in performance is evaluated via simulation. Notice that other

simplified metrics can also be used.

Eq. (2)

$$B_i = |real\{z - \hat{a}_i\}| + |imag\{z - \hat{a}_i\}| \quad i = \begin{cases} 0,1,2,3 & for \quad QPSK \\ 0,1,2,3,4,5,6,7 & for \quad all \quad other \quad constellations \end{cases}$$

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where:

B_i is the branch metric for the i' th subset,

z is the received soft symbol, and

10    $\hat{a}_i$ is the constellation symbol belonging to the i' th subset, which is closest to the

received symbol.

TCM Coding in the Transmitter, Reduced Complexity VA (RCVA) Decoding in the Receiver

15   This is a novel suboptimal receiver operation for a TCM modulation subsystem.
One example is described herein below for an 8-state TCM code used in SCDMA
transmission associated with the Docsis2.0 standard. The present invention is not so
limited however, and it shall be understood the method described is general.

20   The decoder uses a reduced complexity Viterbi algorithm (RCVA), with an 8-
state trellis and 2 or 4 branches leaving each state for QPSK and all other constellations
respectively. Basically there are 8 slicing operations (no slicing for QPSK and 8QAM),
and 8 branch metric calculations (4 for QPSK) for each iteration. For state metric
calculations, there are (4 branch * 8 state) = 32 additions, and for each state, 4

25   comparisons to derive the best previous state. A thorough description and considerations
regarding implementation on DSP is discussed herein below. In RCVA, only the metrics
for the subsets of some (for example four) symbols closest to the received symbol are
calculated. The metrics for all other subsets are set to a predefined ("saturated") value,
set independently for each constellation. For received symbols that are "outside" of the

30   constellation - only two metrics are calculated; metrics for all other subsets (2 for QPSK,

6 for all other constellations) are saturated. The saturation values for each constellation were set according to some preliminary research. Further research may yield better values, but the present inventors believe that this will enhance performance by not more than 0.1 dB. Based on the constellation and the properties of the TCM coding, the

5   number of subsets for which metrics are calculated can be chosen, and respectively the number of subsets that are using saturated metrics is chosen.

In RCVA, the present inventors further used the simplified metrics as in SMVA, described herein before. Following DSP implementation, it is expected that the number

10   of clock cycles needed per symbol to perform the RCVA branch metric calculation can be reduced from 16 to 4. The degradation in performance is evaluated via simulation.

Simulation Results

Based on simulation results, the symbol error rate (SER) for each transmission

15   rate is shown in Figures 4 - 9. For each transmission rate (measured in information bits per symbol), the five plots follow five scenarios, including 1) uncoded operation; 2) TCM coding in the transmitter, VA decoder in the receiver; 3) TCM coding in the transmitter, simplified metric VA (SMVA) in the receiver; 4) TCM coding in the transmitter, reduced complexity VA (RCVA) in the receiver; and 5) TCM coding in the transmitter, simple

20   slicing decoder in the receiver. In each simulation, more than 1,000,000 symbols were generated (with the appropriate number of bytes, according to the constellation size).

Conclusions

The simulation results shown in Figure 4 - Figure 9, suggest that the TCM coding

25   scheme, introduced to SCDMA mode of DOCSIS2.0, yields a coding gain of 2-3dB at le-4 > SER > le-6. The asymptotic coding gain of this scheme at high SNR can be seen to approach 4dB (5dB for QPSK); but on the other hand, when RS-coding is concatenated with TCM, SER=le-4 at the TCM decoder output seems like a reasonable operating point.

30   The simulation results emphasize the negligible performance degradation of using either SMVA or RCVA decoding, instead of a full VA. The degradation is only a few

tenths of a dB, whereas the complexity reduction is up to 12 clock cycles per symbol for a DSP implementation as discussed herein below. In some cases this can enable implementation of a receiver (for example the DOCSIS2.0 S-CDMA burst receiver) on a DSP.

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Implementing a VA for TCM decoding on a DSP

DSP based implementation is based on block base processing. The following is a high-level description of the Viterbi algorithm employed. At each iteration, the following should most preferably be performed:

10   1.   receive soft symbol;

    2.   for each TCM subset, choose the constellation point closest to the received symbol; and

    3.   calculate the squared Euclidean distance of this selected point from the received symbol (steps 2,3 actually choose between parallel branches

15   between states in the trellis, and give branch metrics to each branch).

    4.   Go over each trellis states and calculate new state metrics as the minimum of the sums of all possible (previous state + appropriate branch) that lead to this state.

    5.   (this can be done at each iteration or in a batch manner:) Select the state

20   with the smallest metric, and trace back from this state to decide in the state and appropriate transmitted symbol(s) with delay based on the traceback length.

    6.   Go back to step 1.

Steps 2 and 3 are discussed herein below in further detail, and describe one technique for

25 implementing the known Viterbi algorithm using a DSP.

Trellis parallel paths selection and metric calculation

One example is described herein below for an 8-state TCM code used in SCDMA transmission associated with the Docsis2.0 standard. The present invention is not so

30 limited however, and it shall be understood the method described is general.

Each trellis stage requires choosing the minimal metric out of 2^i parallel paths, where i is the number of uncoded bits in a symbol. This should be done to all 8 subsets for SCDMA. Two methods can be considered:

1) Performing 8 slicer operations, one for each subset. This is a high MIPS

5   consuming option since each slicer operation can use an un-squared constellation requiring 10-12 clocks/symbol/subset.

2) Divide the constellation space to regions, so that trellis metrics located within this region should be calculated related to the same 8 symbols. An example for region partitioning for 16QAM constellation can be seen in Figure 10. For example: "Region 3"

10 line divides the IQ plane into two areas, where all soft decisions falling to the left of the "Region 3" line should be sliced related to symbol "13" (i.e. - uncoded symbol is "1") and all soft decisions falling to the right of "Region 3" line should be sliced related to symbol "03" (i.e. - uncoded symbol is "0"). Using this method for every received symbol, a slicing operation is done based on these regions, where this slicing operation

15 simultaneously selects the best symbol in each of the 8 subsets. The distance between the received symbol and the selected constellation point in each subset is calculated based on the:

a.   Distance of the received symbol and the "region representing point" representing each of the regions (see crosses in figure 10). This is

20   calculated per each received symbol.

b.   b.   Distance of the "region representing point" and the corresponding constellation point in each subset (as the regions were defined, there is only one point per subset). This is calculated a priori, and can be stored in a look-up table.

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Detailed operation (Performance analysis)

Operations required and estimated DSP clock cycles required for a C64x DSP available from Texas Instruments Incorporated of Dallas, Texas are considered.

•   For 16QAM and 64QAM: rotate received symbol by PI/4 so a simple slicing

30 operation would determine the relevant region MIPS estimation: ~1 clock/symbol.

- Perform saturation for the rotated symbol so only relevant regions would be generated after slicing. For example, in Figure 10, saturation is required to achieve only 16 valid slicer outputs. For very large constellations, neglecting this step might be possible and will result in negligible performance degradation. MIPS estimation: ~1 clock/symbol.

- Perform slicing operation. MIPS estimation: Only square constellation slicing is required for all possible constellations, resulting with -3-4 clocks/symbol.

- Find distance from received symbol to region center ("Initial_Distance "). MIPS estimation: This involves subtraction for I and Q. ~1 clocks/symbol.

- Use region decision as an index for a look-up table. This table holds for each region the distances from region center to each of the 8 constellation point within that region. Add each loaded metric to Initial_Distance and raise to the power. Add I squared distance to Q squared distance. Store 8 generated metrics to Viterbi memory. MIPS estimation: 2[clocks/region points]*8[points in a region] = ~16 clocks/symbol.

  o Using SMVA reduces this to ~8 clocks/symbol since the squaring operation is not done.

  o Using RCVA further reduces this to ~4 clocks/symbol since this is done only for 4 subsets instead of 8.

Memory estimation: All the regions for all constellations are required to be in memory. The numbers of regions is 16, 25, 144, 169 for 16QAM, 32QAM, 64QAM and 128QAM respectively. Therefore the total number of required regions is 354 regions. Assuming each region holds for each symbol 12 bits/dimension, the required memory is 354 [regions] * 8 [metrics/region] * 2 [I/Q] * 12/8 [bytes/metric] = ~8.5 Kbytes

TOTAL MIPS and memory estimation: Regular operation: ~22-23 clocks/symbol, ~8.5 Kbytes.
SMVA: ~14-15 clocks/symbol, ~8.5 Kbytes.
RCVA: ~10-11 clocks/symbol, ~8.5 Kbytes.

In view of the above, it can be seen the present invention presents a significant advancement in TCM decoding techniques. It should be apparent that the present invention represents a significant departure from the prior art in construction and operation. However, while particular embodiments of the present invention have been
5   described herein in detail, it is to be understood that various alterations, modifications and substitutions can be made therein without departing in any way from the spirit and scope of the present invention, as defined in the claims which follow. For example, although a DSP implementation of a VA/SMVA/RCVA has been described in detail herein before, the present invention is not so limited, and can easily be extended to many
10   other implementations.